

Appendix G

Use of Soil Cement for Levee Protection

G-1. Purpose

The purpose of this appendix is to provide guidance on the design and construction of soil cement slope protection for levees and embankments. This includes soil cement, materials, mixture proportioning, design of slope protection, construction, quality control, inspection, and testing.

G-2. General Considerations

a. Soil Cement. The American Concrete Institute defines soil cement as a mixture of soil and measured amounts of portland cement and water compacted to a high density. Soil cement can be further defined as a material produced by blending, compacting, and curing a mixture of soil/aggregate, portland cement, possibly admixtures including pozzolans, and water to form a hardened material with specific engineering properties.

b. Application. Although riprap has historically been used for slope protection for levees, dams, channels, etc., there are situations when suitable rock is not available within economical haul distances and soil cement slope protection may be the most economical and appropriate selection.

c. History. The use of soil cement for slope protection has increased considerably over the past 30 years. The main focus of this effort has come from the U.S. Bureau of Reclamation (USBR) in the construction of dams. The first experimental use of soil-cement for slope protection was a test section constructed by USBR at Bonny reservoir in eastern Colorado in 1951. Observation of the performance of this test section for the first 10-year period of service indicated excellent performance of the soil cement which was subject to harsh wave action and repeated cycles of freezing and thawing. This led to the conclusion that use of soil cement for slope protection was feasible based on both economical and service life considerations.

d. Economics. The decision to use soil cement instead of riprap is primarily an economic one. However, not every soil is suitable for producing soil cement for this application. Therefore, the designer must compare the availability of suitable soil for soil cement versus the availability of suitable rock for riprap. The designer must prepare a cost analysis in arriving at a decision. Factors that must be considered for soil cement include cost of cement, location of suitable soil, special processing requirements if needed, haul distance, dimensions and configuration of the slope protection and mixing and placement methods. For riprap, considerations include cost and availability of rock, size and availability of rock, haul distance, special processing requirements, configuration of placement and placement effort. Cost estimates of the alternative methods provide the basis for the economic analysis.

G-3. Materials

a. Soils. In general most soils of medium to low plasticity (Plasticity Index (PI) equal to or less than 12) can be used for soil cement. However for levee protection, better quality granular materials are recommended since the soil cement may be subjected to repeated cycles of wetting-drying, freezing-thawing and wave action. It is recommended that the soil should not contain any material retained on a 2-in. (50.8 mm) sieve, nor more than 45 percent retained on a No. 4 (4.75-mm) sieve, nor more than 35 percent or less than 5 percent passing the No. 200 (0.075-mm) sieve. The PI should be equal to or less than 12 and

the organics content should be less than 2 percent. It should be noted that clay balls (nodules of clay and silt mixed with sand materials) can form when the PI is as low as 8. Clay balls can be detrimental when soil cement is exposed to weathering and the clay tends to wash out leaving voids in the soil cement structure. Clay balls greater than 25.4 mm (1-in.) should be removed and the minus 25.4-mm (1-in.) clay ball content should be limited to 10 percent. For economic reasons, the soil should be obtained from a borrow area close to the construction site. Samples from borrow sources must be evaluated for gradation and PI. If in-situ soils are not suitable it may be necessary to blend materials from several borrow sources.

b. Cement. Portland cements meeting specifications of ASTM C 150 are suitable. Generally, Type I is used for soil cement. However, soil cement can be subject to sulfate attack and it is the lime in the cement that is involved in the reaction. Therefore, sulfate bearing soils or water should be avoided. There is no definitive test to determine the threshold sulfate content at which a soil is deemed to be potentially reactive however experience has shown that soils with a sulfate content as low as 0.3 percent have developed reactions. If exposure to sulfates is not avoidable, Type II cement is recommended. Use of fly ash as a replacement for portland cement is not recommended in that experience has indicated that fly ash reduces early age compressive strength and durability when used in soil cement.

c. Water. Most water is acceptable for soil-cement. The primary requirement is that water should be free from substances deleterious to hardening of the soil cement. Specifically, water should be free from objectionable quantities of organic matter, alkali, salts, and other impurities. Presence of soluble sulfates should be of concern. Seawater has been used satisfactorily. The presence of chlorides in seawater may increase early strength. The quality of water for soil cement should be similar to that used for mixing concrete. Guidance on water quality may be found in Corps of Engineers CRD-C 400.

G-4. Proportioning Soil Cement Mixtures

a. General. One of the key factors that accounts for the successful use of soil cement is careful pre-determination of engineering control factors in the laboratory and their application during construction. The composition of soils varies considerably and these variations affect the manner in which the soils react when combined with portland cement and water. The way a given soil reacts with cement is determined by simple laboratory tests conducted on mixtures of cement, soil, and water. These tests determine three fundamental requirements for soil cement: the minimum cement content needed to harden the soil adequately; the proper moisture content; and the density to which the soil cement must be compacted. Generally, the procedure to determine the mixture cement content consists of the following steps: soil classification test to determine an appropriate soil type; moisture density tests at a selected initial cement content to determine target density and water content values; durability tests at a range of cement content values including the initial cement content; unconfined compressive strength tests; and selection of final cement content based on test results.

b. Selection of soils. The design of a soil cement mixture begins with selection of a suitable soil type. The objective is to select a soil that can be stabilized with the minimum cement content and that will be suitably durable for the range of service conditions to which it will be subjected. Guidance on specifications for grading and plasticity of soils were given previously. Generally, soil cement made with granular materials requires less cement than soil cement made with sands and fine grained soils. The latter materials are also less durable. If the soils available in the immediate area of construction do not meet desired specifications it may be necessary to blend several soil types to obtain the desired characteristics. However, before blending is specified, the increased costs of processing and monitoring should be compared to the increased cost of additional cement required for the natural material. Occasionally the designer may encounter soils that are unreactive or are marginally reactive requiring apparently excessive amounts of cement. Often such soils contain acidic organic materials that affect the reaction.

c. *Cement content general.* A series of laboratory tests must be conducted to determine cement content. Inherent in these tests is also the determination of design soil density and water content. If the project is large and more than one candidate soil is available, it may be appropriate to conduct the entire series of tests on each soil to determine the most economical mixture for the project. Also, if several borrow areas having significantly different soils are involved it may be necessary to conduct laboratory tests on soil from each borrow area to determine the appropriate mixture for each soil. The tests involved in this process include: moisture density tests (ASTM D 558) to determine initial design density and moisture content based on a selected initial cement content and durability tests (ASTM D 559 and D560) to determine resistance to repeated cycles of wetting and drying and freezing and thawing which might be expected under natural climatic changes. Compressive strength tests (ASTM D 1632 and D 1633) should be conducted on laboratory prepared specimens. Tests are conducted at several cement content values and the final cement content is that which produces the required durability and strength at the lowest practical cement content. Strength and rate of strength gain are important factors in performance of the soil cement. Adequate strength is required to resist forces of wave action and uplift pressures.

d. *Moisture density tests.* Moisture density tests are conducted to determine values of density and water content for molding soil cement durability samples and for field control of compaction during construction. The cement content for moisture density tests is selected based on soil classification. Soils should be classified following procedures indicated in ASTM D 2487, Standard Test Method of Classification of Soils for Engineering Purposes. Initial cement contents for different soil classifications are indicated in Table G-1. The appropriate value of cement content for moisture-density tests may be selected from this table. Only coarse grained soil symbols are shown as these are the soil types preferred for soil cement for slope protection. Representative soil samples should be collected and moisture density tests conducted following procedures indicated in ASTM D 558, Standard Test Methods for Moisture Density Relations of Soil Cement Mixtures. Results of the tests are plotted as shown in Figure G-1 from which values of dry density and moisture content are selected for molding durability specimens. The dry density may be the maximum or a percentage of the maximum density indicated on the plot. Past experience has indicated that a minimum density of 98 percent of the maximum ASTM D 558 density is adequate. The water content is the value associated with the selected density. The water content at maximum dry density is termed the "Optimum Water Content" (OWC).

Table G-1
Initial Cement Content for Moisture Density Tests

Soil Classification (ASTM D 2487)	Initial Cement Content (percent dry weight of soil)
GW, GP SW, SP	7
GM, SM	8
GC, SC	9
SP	11

e. *Durability tests.* Two types of durability tests are conducted: ASTM D 559, Standard Test Methods for Wetting and Drying of Compacted Soil Cement Mixtures and ASTM D 560, Standard Test Methods of Freezing and Thawing of Compacted Soil Cement Mixtures. These tests were designed to reproduce in the laboratory the moisture and temperature changes expected under field conditions. These tests measure the effect of internal volume changes produced by changes in moisture and temperature. From these tests the minimum cement content required to produce a structural material that will resist volume changes produced by changes in moisture and temperature can be determined. Wet dry tests should be conducted in all geographic areas. Freeze-thaw tests should be conducted in all areas that experience at least one cycle of freezing and thawing per year since levee protection is expected to be subjected to this condition over a long

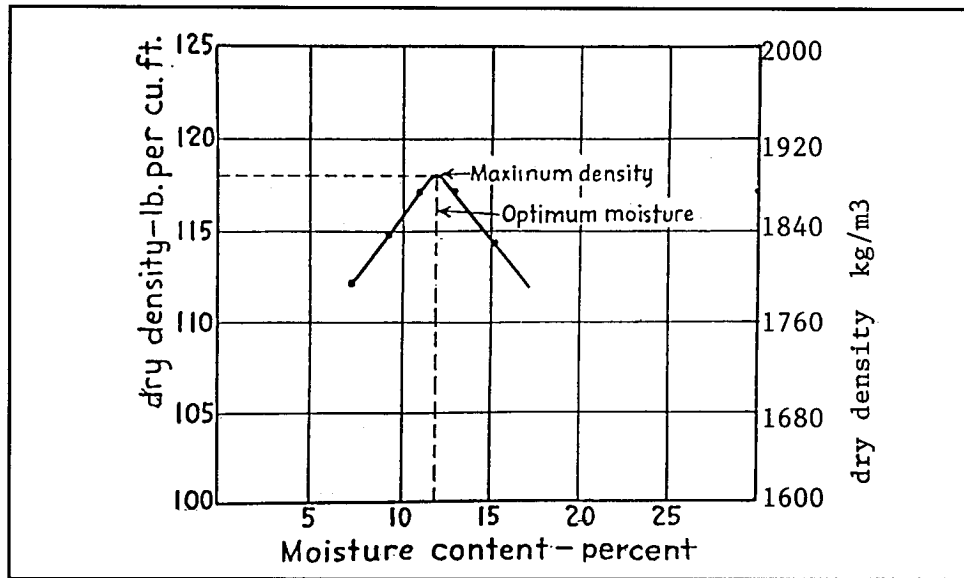


Figure G-1. Typical moisture-density curve

period of time. If there is absolutely no expectancy of freeze thaw cycles in the geographic area this test may be omitted. Each type of test consists of twelve two-day cycles of wetting/drying or freezing/thawing as appropriate and thus requires 24 days to complete.

For each type of test, duplicate specimens of soil cement should be prepared at cement contents equal to the cement content used for the moisture density test and at cement contents 2 percent above and 2 percent below that used for the moisture density test. For example, if the cement content for moisture density tests is 7 percent, samples for durability tests should be molded at 5, 7, and 9 percent cement. Ideally, a moisture-density test should be conducted for each cement content to determine maximum density and optimum moisture water content for that particular design mixture since these values vary with cement content. If this is not possible the density and moisture content determined from the initial tests may be used.

After each cycle (of either the wet-dry or freeze-thaw) the specimen is scrubbed with a wire brush to remove soil cement that becomes loosened or unbonded as a result of exposure to the test environment. After the twelve cycles are completed, the total weight loss is calculated and this value is compared to established criteria. The weight loss criteria are shown in Table G-2. Assuming both tests are conducted, specimens must meet both criteria. If specimens do not meet both criteria, adjustments must be made in the soil gradation and/or cement content based on engineering judgment and at least one set of tests should be rerun. Adjustments may include blending of aggregate to the soil and/or increasing the cement content.

Table G-2
Durability Test Weight Loss Criteria

Type of Durability Test	Maximum Weight Loss After 12 Cycles (percent)
Wet Dry (ASTM D 558)	6
Freeze Thaw (ASTM D 559)	8

f. Unconfined compressive strength tests. The next step is to conduct unconfined compressive strength tests (ASTM D 1632 Making and Curing Soil Cement Compression and Flexure Test Specimens in the Laboratory, and ASTM D 1633 Compressive Strength of Molded Soil Cement Cylinders). Strength of the soil cement is important in slope protection to provide resistance to wave action and uplift pressures. In fact, strength may be the determining factor in arriving at the final design cement content. Experience has shown that often the cement content of specimens meeting compressive strength criteria is higher than that necessary to meet durability requirements. The cement content for specimens for initial compressive strength tests will be the minimum cement content of the specimens that met durability criteria. The water content and dry density will be that used to mold durability specimens. Duplicate specimens should be prepared and tested as indicated according to the ASTM procedures previously indicated. Minimum compressive strength criteria are indicated in Table G-3. If strengths of specimens tested at the initial cement content do not meet minimum criteria, then the cement content should be increased in two percentage point increments and compressive strength tests rerun until criteria are met or it is determined that another mix design approach must be undertaken. If time constraints do not permit conduct of unconfined compressive strength tests until the durability tests have been completed, it may be necessary to conduct these tests simultaneously. If this is necessary, the unconfined compressive strength tests should be conducted on specimens prepared at all of the cement contents used in the durability tests. This approach obviously requires that many more specimens be prepared and tested however the savings in time may be more economical than conducting the tests in sequence.

Table G-3
Unconfined Compressive Strength Criteria (ASTM D 1633)

Cure Time (days)	Minimum Compressive Strength, kPa (psi)
7	4138 (600)
28	6034 (875)

g. Final cement content. The final cement content is the minimum cement content used in specimens that met or exceeded both the durability and compressive strength criteria. Some designers have added one or two percentage points to this cement content to account for variability in the field cement content where the proposed method of construction is mixed in place. Where central plant mix procedures are used control of cement content is generally accurate.

G-5. Design of Slope Protection

a. General considerations. Design of slope protection with soil cement is somewhat similar to design with riprap in that protection must be provided against erosional forces from wave action and stream currents. Soil cement slope protection can be provided in two configurations: stair step or plating. In stair step slope protection the soil cement is usually placed in successive horizontal layers adjacent to the slope. This method is preferred for slopes exposed to moderate to severe wave action or debris carrying, rapidly flowing water. The plating method consists of placing one or more layers of soil cement parallel to, i.e., directly on, the slope. This method is used where less severe exposure is expected.

b. Stair step method. The stair step method consists of constructing successive horizontal lifts of compacted soil cement up the slope to the desired height of protection (Figure G-2). Each successive lift is set back by an amount equal to the compacted lift thickness times the cotangent of the slope which results in a stair step pattern approximately parallel to the embankment slope. Layer thickness can be from 152.4 to 304.8 mm (6 to 12 in.) depending on the type of compaction equipment used. Historically, stair step construction has been accomplished with 152.4 mm (6 in.) compacted lifts. However, thicker lifts require less

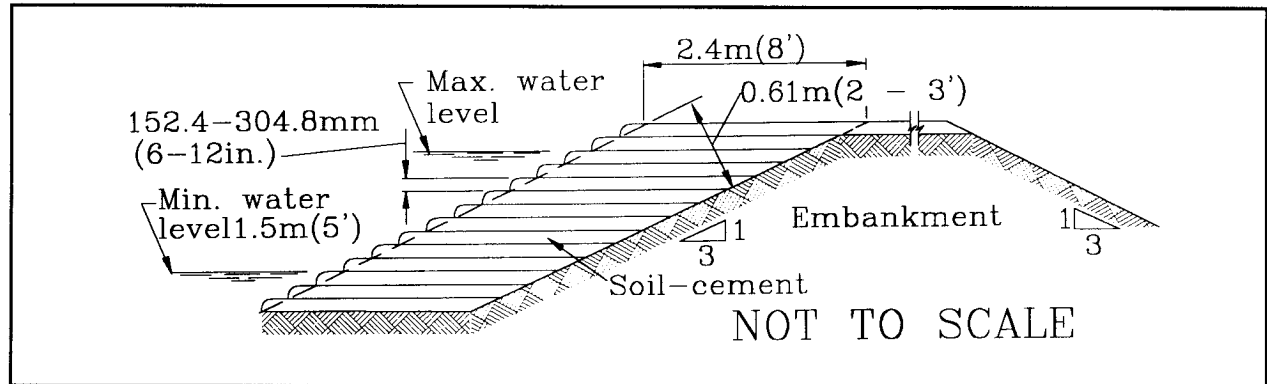


Figure G-2. Stair-step method of slope protection

construction effort and result in fewer bond surfaces. The disadvantage of thicker lifts is more loss of soil cement at the exposed edge during construction and additional effort is required to obtain desired density throughout the lift. The width of the layer also is a function of type and size of construction equipment. Experience has shown that a layer width of about 2.4 m (8 ft) is generally most convenient. Since stair step protection is indicated for more severe environmental conditions, a thicker covering over the slope is generally specified. Experience has indicated that the total thickness of soil cement measured perpendicular to the slope should be 0.61 to 0.92 m (2 to 3 ft). The relationships between slope, facing thickness, layer thickness and horizontal layer width are shown in Figure G-3.

c. Plating method. The plating method consists of lifts placed parallel to, i.e., directly on, the slope and is used in areas where a thinner facing is required. Generally two 152.4 mm (6-in.) lifts or one 203.2-mm (8-in.) lift are used for plating. One of the primary considerations in plating protection is providing resistance to high flow especially with debris. To date there are no definitive design criteria to determine lift thickness based on abrasion, however, since the plating method is applicable for areas subjected to less harsh environments, experience has shown 304.8 mm (12 in.) of protection is adequate. In the plating method, lifts can be constructed so that the resulting construction joints are either parallel or perpendicular to the flow of water. If placement and compaction of the soil cement are up and down the slope, the construction joint will be perpendicular to the water flow. If placement and compaction are along the slope, the construction joints will be parallel to the flow of water. For the plating method of construction, the slope should be 3H:IV or flatter in order to properly spread and compact the soil cement. Construction on steeper slopes may be accomplished if special compaction equipment is used.

d. Freeboard and wave runup. Freeboard is the vertical distance from the top of the levee to the water surface. The freeboard should be sufficient to prevent waves from overtopping the levee or damaging the crest. Slope protection should be provided in the freeboard area to prevent erosion. When a wave contacts the face of the levee it will run up the slope. Wave run up is the vertical height above the still-water level to which the uprush from a wave will rise on a structure. It is not the distance measured along the inclined surface. To calculate the wave run up for soil cement slope protection, the wave run up value based on riprap protection is first calculated and this value is multiplied by a factor based on the type and condition of the soil cement slope protection. For calculation of wave run up for riprap, designers should consult the following references: EM 1110-2-1614, Design of Coastal Revetments, Seawall, and Bulkheads, dated 30 June 1995; and the Automated Coastal Engineering System (ACES) computer program. For stair step construction with vertical faces on the layers the run up factor 1.2. Where the faces have become rounded due to weathering and erosion the run up factor is 1.3. For plating slope protection the run up factor is 1.4.

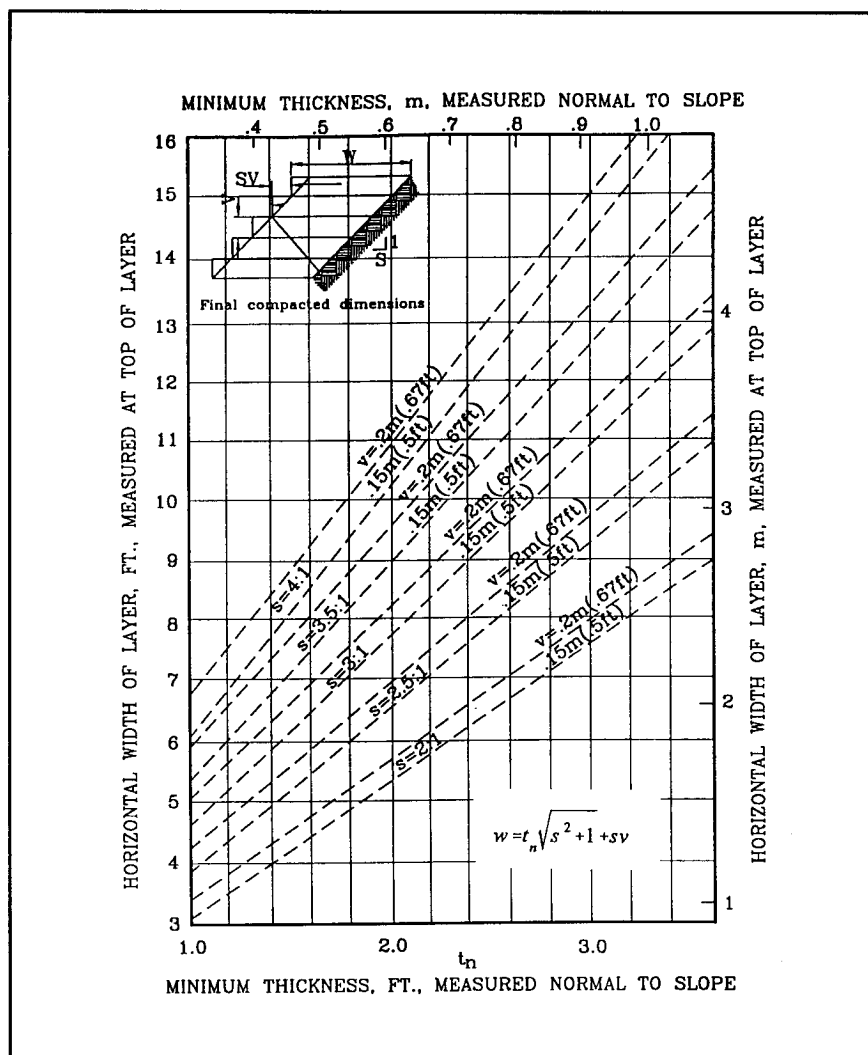


Figure G-3. Relationship of slope, facing thickness, layer thickness, and horizontal layer width

e. Transitions. Transitions between soil cement and earth or other structures should be addressed. Tie-backs similar to riprap emplacements can be designed to avoid flanking of the structure. An alternative is to use a riprap section at either end of the soil cement structure. Where soil cement joins other structures and compaction is difficult it may be appropriate to use lean concrete.

f. Drainage and seepage. Although no distress to soil cement slope protection due to rapid drawdown has been reported and the current thinking is that drainage is not required unless severe drawn down is anticipated, the designer should be aware of the preventative measures can be used. Three concepts are presented. One is design of the levee so that the least permeable zone is adjacent to the soil cement. This will provide protection against build up of excess pore water pressure. A second method is to determine that the weight of the facing is sufficient to resist uplift pressures. Here, there may be some pore pressure relief through shrinkage cracks in the soil cement. Obviously, some estimate must be made of the gross hydraulic conductivity of the soil cement. A third measure is to provide deliberate drainage conduits through the soil cement. This approach was used by the Bureau of Reclamation at Meritt Dam. Three rows of 76.2- to

127-mm- (3- to 5-in.-) diameter weep holes were drilled into the facing after construction and included 118 holes on 3.05 m (10 ft) centers. In such arrangements, a filter is placed in the area of weep hole before soil cement construction.

G-6. Construction

a. General. There are two general methods in common use for constructing soil-cement: mixed-in-place and central mix plant. Regardless of the equipment and methods used the goal is to obtain thoroughly mixed and adequately compacted and cured soil-cement. The central mix method involves mixing of a borrow material with cement and water, at a centrally located plant. The mixture is then transported to the site. The mixed-in-place method involves mixing of cement and water with the in-place soil at the site, and is infrequently used for embankment soil cement applications.

The most common method of soil-cement construction for bank protection is central mix plant. For soil-cement used as bank protection, particularly where banks experience higher flow velocity forces, adequate strength and durability, and consistent quality, are primary requirements. It is harder to achieve these objectives using mixed-in-place construction than central mix plant.

Two methods are used for placement and compaction of soil cement for embankments: stair step or plating. Design for these methods was discussed earlier in this document. The stair step method is the predominant method used, although construction using both methods is discussed in the subsequent sections on spreading and compaction.

Soil cement should not be mixed or placed when the soil or subgrade is frozen or when the air temperature is below 9°C (45°F). Specifications may allow soil cement construction to proceed if the air temperature is at least 4°C (40°F) and rising. Hot weather poses a few problems for soil cement construction, requiring sometimes additional moisture application to the materials, faster placement and compaction operations, and additional curing effort.

b. Central mix plant construction. There are two basic types of central mix plants: pugmill mixers either continuous or batch type, and rotary drum mixers (also a batch type of mixer). The uniformity of soil cement produced by these plant types is generally roughly equivalent, provided they have been properly calibrated. Continuous mix pugmill plants have higher production rates, while batch plants are often easier to calibrate, and require less frequent calibration. Batch-type pugmill plants have been used, but infrequently. Production rates between 76.4 and 152.9 m³ (100 and 200 cu yd/hr) are common for stair-step soil cement construction. The basic steps of central mix plant construction of soil cement are: subgrade preparation, borrow materials, mixing, transporting, spreading, compacting, bonding lifts, finishing, construction joints, and curing and protection.

(1) *Subgrade preparation.* A firm subgrade is necessary to compact the overlying layers of soil cement to the required density. The subgrade is prepared by removing and replacing, or stabilizing, soft or wet areas, removing deleterious materials, and grading and compaction to construction plans and specifications. Most overly wet subgrade areas can be corrected by aerating and recompacting, or some type of chemical stabilization. Dry subgrades are surface moistened immediately prior to soil-cement placement.

(2) *Borrow materials.* Soil borrow sources are usually near the construction site and may consist partially or wholly of excavated bed and/or bank material. Native borrow materials are naturally variable in composition. Excavation, blending and stockpiling methods for borrow material should be selected to minimize this variation, and produce as consistent a material as possible. Horizontally stratified soil layers can be blended by deep excavation using full face cuts, insuring all layers are cut with each equipment pass.

If materials vary laterally across the borrow areas, loads from different locations should be blended in a systematic fashion. Further blending can also be done as materials are brought to the plant stockpile area. Alternating the loads from different parts of the plant stockpiles, or even using a front-end loader to take a vertical cut of the stockpiles, also helps blend materials as they are fed to the mixing plant.

Screening the borrow material through a 25-mm (1-in.) to 38.1-mm (1-1/2-in.) mesh at the pit or at the plant can help remove oversize clay balls and other oversize materials. Selective excavation may be necessary to avoid excessive clay balls or clay content in the borrow area.

Stockpiles should be separated from each other and all plant equipment by at least 15.2 m (50 ft). Where the soil contains coarse aggregate, stockpiling is done in layers to minimize segregation.

(3) *Mixing*. Central mixing plants with rated capacities of 227 to 907 metric tons (250 to 1,000 tons) per hour (about 95.56 to 382.3 m³ (125 to 500 cu yd)) are used commonly. Special blending requirements may require several stockpiles and separate storage feeder bins. Prior to mixing and placing, it is necessary to measure the quantities and proportions of material supplied by the plant. The plant should be accurately calibrated.

(a) *Pugmill mixers*. The most common continuous mixing plants contain a twin shaft pugmill. Figure G-4 shows a diagram of a typical pugmill central mix plant. USBR recommends a twin-shaft pugmill with a rated capacity of at least 152.9 m³ (200 cu yd)/hr. A pugmill mixing chamber contains twin shafts rotating in opposite directions, with paddles (see Figure G-5) that force mix the soil cement and move it through the chamber by the pitch of the paddles. Material feeds (by adjusting gate openings and belt speed) and pugmill features (such as pugmill tilt and paddle pitch) may be adjusted to optimize the mixing actions and production. Thoroughness of blending is partly determined by the length of mixing time. A mixing time of 30 sec is commonly specified, although shorter times have also been shown to be adequate, depending on the mixer efficiency.

Batch type pugmill mixers, where the materials are delivered to a pugmill mixer in a discrete batch rather than as a continuous ribbon of material, can provide effective mixing of soil cement, but are seldom used, largely due to lower production capacity and lack of availability.

(b) *Rotary drum mixers*. Although rotary drum (also called tilt drum) mixers are sometimes used, they are generally lower in production capacity than pugmill mixers. These plants are typically converted central mix concrete plants, and function in the same manner. Mixing times for these plants are typically about 60 sec.

(4) *Transporting*. Haul trucks can be of the end or bottom dump variety, although many types are used. Where conditions are extremely hot and/or windy or where sudden showers are a possibility, soil cement should be protected by using canvas covers on haul vehicles. Equipment should be clean. The elapsed time between mixing and compacting should be kept to a minimum. Sixty minutes is usually the maximum. Therefore, most specifications require haul times to be kept below a maximum of thirty minutes.

In stair step construction, temporary ramps are constructed at intervals along the bank to enable trucks to reach the layer to be placed. These temporary ramps should have a minimum 0.457 m (18-in.) thickness of material to protect the edge of the previous lift from truck traffic. There is also a requirement, where streambeds are dry, for ramps to be spaced to allow egress from the channel in case of a flood. These are constructed at 45° angles, with a minimum of 0.61 m (2 ft) of cover over the soil cement, and spaced about 91.4 to 121.9 m (300 to 400 ft) apart.

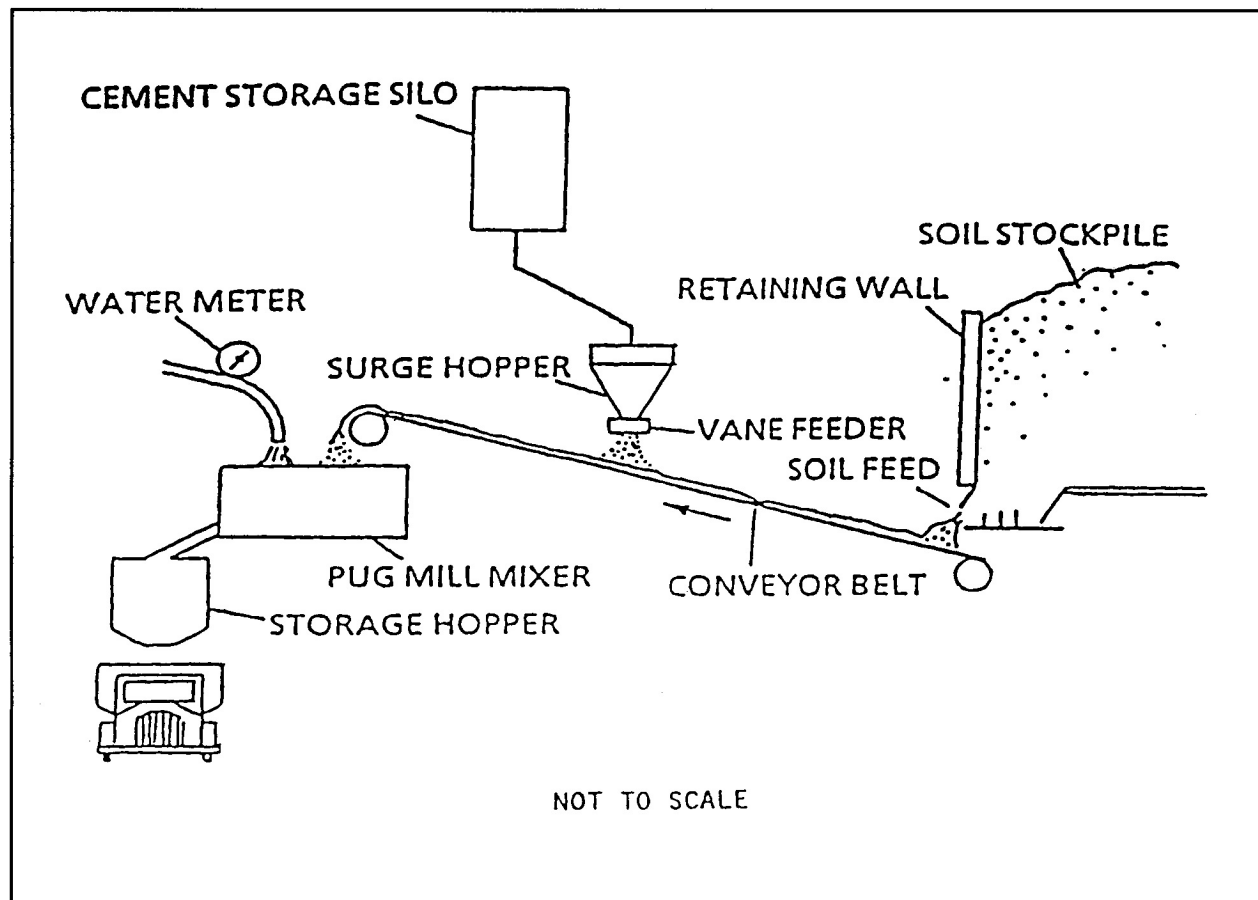


Figure G-4. Typical pug mill central plant



Figure G-5. Mixing paddles of a twin-shaft, continuous-flow central mixing plant

Figure G-6 shows a typical step-construction sequence. Frequently time and cost savings have been realized by using conveyor systems to deliver the soil cement to the spreader. This removes the necessity for ramp construction and truck maneuvering and provides a cleaner end product. Narrower layers and plating applications can also be placed using a conveyor system. The soil cement can be delivered from above or below directly to a spreader box.

(5) *Spreading.* Soil cement must be spread in a manner that will provide a compacted layer of uniform thickness and density, conforming to the design grade and cross section.

(a) *Stair step method.* There are a wide variety of spreading devices and methods for stair

step construction. One of the most common is the spreader box attached to a dozer or grader. An

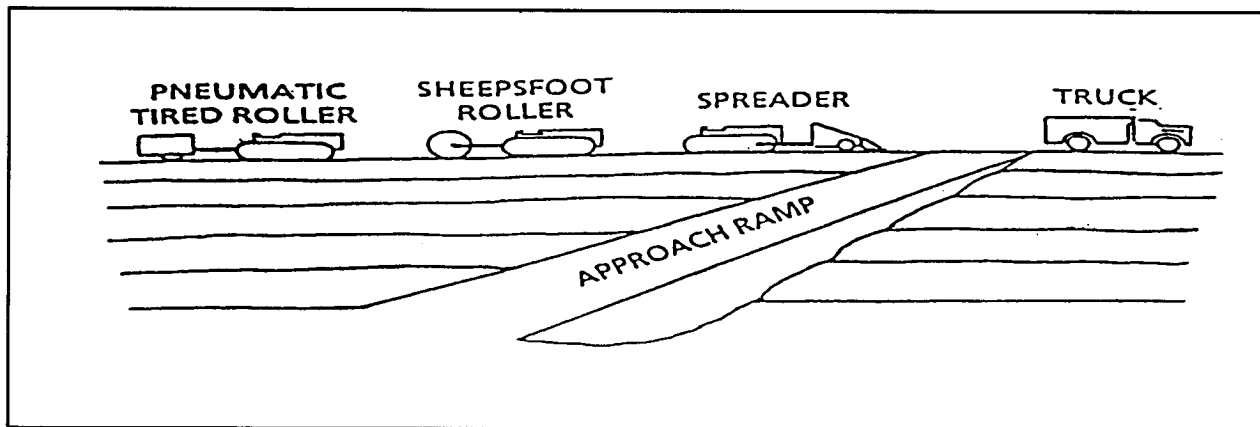


Figure G-6. Typical construction sequence

alternate method is to place material in windrows to be spread by a grader. Care must be taken with the windrow operation not to over manipulate the material which may cause separation and premature drying. Layers are spread 15 to 30 percent greater than the required compacted thickness. Experimentation may be necessary to determine the appropriate spread thickness since different combinations of equipment and soil type may produce different amounts of precompaction. Spreading may also be done with asphalt-type or RCC pavers. Some of these pavers are equipped with one or more tamping bars which provide some initial compaction.

Placement of stair-step sections may need to be limited to a maximum of 1.22 m (4 ft) height in a single shift to avoid instability producing bulging in the outer face from the surcharge weight of material and equipment above.

(b) *Plating method.* A variety of methods may be used for spreading of soil cement for plating applications. On relatively level surfaces, the methods are the same as for stair step placement. Plating construction on steeper slopes requires different procedures than stair step construction. Dozers are commonly used to spread soil cement on steeper slopes. USBR has reported best results in terms of producing uniform thickness and minimum waste when soil cement was spread from the top to the bottom, rather than from bottom to top. Whatever method is used, careful attention needs to be paid to achieving uniform thickness.

(6) *Compaction.* Minimum compaction to be achieved in the field is normally specified as a percentage of maximum density determined by ASTM D 558 or ASTM D 1557, typically requiring 98 percent of maximum density. Moisture content of the soil cement mixture must be controlled within tight limits to ensure consistent optimum conditions for compaction. USBR practice has been to place soil cement at water contents at or slightly dry of optimum. This can help avoid excessively wet mixes that may cause traffic and compaction difficulties, as well as lift distortion and increased cracking due to shrinkage. Compaction should begin as soon as possible and be completed within about one hour after initial mixing. No section of soil cement should be left unworked for longer than 30 min. Climatic conditions at some sites, such as very cool, humid weather, may allow relaxation of this guidance. Moisture loss by evaporation during hot weather compaction should be replaced by light applications of water. Compaction is done by various types of rollers. For fine grained soils, a sheepfoot roller is generally used for initial compaction, followed by a pneumatic-tire roller for final compaction. USBR practice has often been to compact the lower portion of the lift with a towed sheepfoot roller, using the vibratory steel-wheeled roller for the upper portion of the lift. Some problems have been encountered with vibratory roller compactors when used for finer grained materials. Vibratory rollers may create fine transverse cracks in the soil cement surface, requiring a

rubber-tired roller for final compaction to close most of the cracks. Compacting soil cement at or above optimum moisture can produce rutting from pneumatic tire rolling. For coarse grained soils, vibratory steel-wheeled or heavy pneumatic rollers are generally used. Compacted layer thickness is typically from 152.4 to 228.6 mm (6 in. to 9 in.), although greater thicknesses of coarse grained soils can be compacted with heavy equipment designed for thicker lifts. The specified minimum density must be achieved throughout the lift thickness, regardless of the lift thickness and compaction equipment used. Compactor weight, and vibration amplitude and frequency must be adjusted during construction to obtain the best compaction. Test sections are a valuable aid in determining the optimum compaction equipment characteristics and procedures.

(a) *Stair step method.* Compaction of the outer edge of the layer is usually not necessary from the standpoint of structural integrity. However, uniform edges provide a better appearance and allow for easier emergency egress from streambeds. Sharp edges reduce wave runup but increase roughness. Edge compaction can be accomplished by hand tampers or through the use of some type of edge support during compaction.

(b) *Plating method.* Compaction is done with various roller types. Construction on near horizontal surfaces is similar to layered construction. Compaction on steeper side-slopes requires different procedures. A rolling deadman (Figure G-7) has been used to winch the roller up and down slope. Adequate compaction has been achieved using bulldozers, although their use is not recommended. Multiple overlapping passes are usually required. Surface tearing can be minimized by using cut grousers or street pads. Compaction from bottom to top has been most successful.

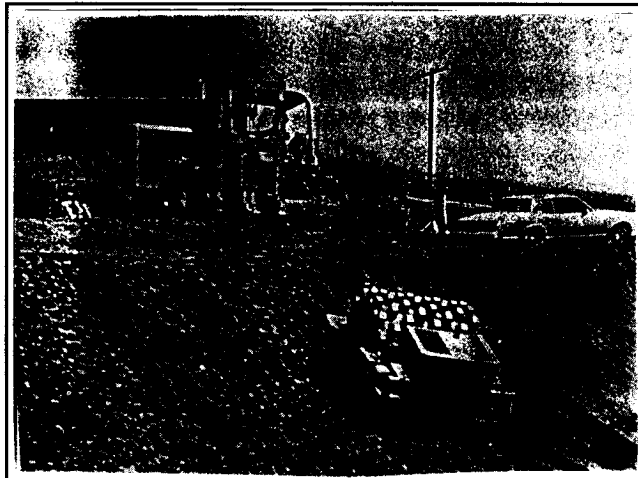


Figure G-7. "Deadman" pulling vibratory sheepfoot roller up the slope

(7) *Bonding lifts.* The bond between soil cement layers is generally weak. No definite criteria is available on the most effective methods of bonding between layers; however, bonding may be considered if layer separation is anticipated. Layer separation may be a concern from strong wave action, or at the upper lift of some sections, where there is little weight above the lift to mobilize shear resistance. The most significant factor in bond strength is time delay between lifts. The shorter the time between lifts the better the bond. Long placements may be broken up into shorter segments, enabling subsequent lifts to be placed more rapidly. Moist curing increases the bond strength but excess water tends to decrease it. Most specifications require temporarily exposed surfaces to be kept moist and clean. Care must be taken to avoid tracking clay or other materials onto

the layer which would reduce bond.

Power brooms should be used for lift surface cleaning to remove loose and unbonded material. USBR studies have suggested that roughening the lift surface with steel power brooming does not significantly contribute to increased bond strength. Brooming is not permitted prior to 1 hr after compaction to allow adequate set of the soil cement.

Both dry cement and cement slurry lift bonding have been used and evaluated in USBR test sections, with encouraging results. A slurry mix should have a water/cement ratio of about 0.70 to 0.80 and an application

the latter rate. Dry cement applications have a disadvantage of being susceptible to wind, while cement slurry is susceptible to rapid drying. Whichever method may be used, the material should be applied immediately before placement of the next lift.

(8) *Finishing.* As compaction nears completion the entire layer should be shaped to specified lines, grades, and cross sections. Edge shaping can be done with a modified blade or a curved attachment on the roller. The lift may require scarification to take out imprints left by equipment or to remove thin surface compaction planes. Scarification can be done with a variety of spring tooth or spike toothed harrows, or similar equipment. Soils containing gravel may not require scarification. Final surface compaction following scarification is performed with a steel-wheeled roller in nonvibratory mode, or a rubber-tired roller. A smooth “table top” finish is not required and may be detrimental to lift joint shear strength. Wheel marks are acceptable, although they may make lift joint cleanup more difficult.

The edges on stair-stepped soil cement applications have been finished by cutting back the uncompacted edges, by using special rounded attachments on compaction equipment, and by leaving sacrificial uncompacted edge material in place to be eroded later.

(9) *Construction joints.* Construction joints are required at the completion of each day’s work or when work must be stopped for time periods longer than allowed for placement and compaction of fresh soil cement. They are made by cutting back into the finished work to proper crown and grade. The joint must be vertical, full depth, and transverse to the layer direction and is usually done with the toe of a grader blade or bulldozer blade. Care must be taken that no debris is present on the joint edge, and that new material placed against the joint adheres to the previous work. Joints should be staggered to inhibit cracking throughout the structure.

(10) *Curing and protection.* Proper curing is essential, because strength gain and durability is dependent upon time, temperature and the presence of moisture. All permanently exposed surfaces should be moist cured for a period of seven days. Traffic should be kept off the soil cement during the curing period. Light traffic is sometimes allowed on the completed soil cement, provided the curing is not disrupted.

Soil cement must be protected from freezing during the curing period. Insulation blankets, straw, or a soil cover are commonly used. Light rainfall should not interrupt construction. However, a heavy rain prior to compaction can be detrimental. For mixed-in-place operations, if rain falls during the cement spreading operation, the cement already spread must be quickly mixed with the soil, and compaction must proceed immediately. After soil cement has been compacted, rain will seldom have detrimental effects.

(a) *Moist curing.* Water curing may be done with fog spraying, or with weighted and secured plastic sheeting if wind is not a problem. Wet burlap can also be used if a moist condition can be maintained. A minimum of 152.4 mm (6 in.) of moist earth can be specified as an alternative. The earth cover may also inhibit freezing should colder temperatures be expected.

(b) *Bituminous membrane curing.* Membrane curing using some types of bituminous material (generally an emulsified asphalt) can be used as an option to water curing where no succeeding layers will come in contact with the membrane. However, the black color may be objectionable to owners. Bituminous membrane curing should not be used for levees, ponds or reservoirs which will have water frequently in contact with the membrane, without evaluation of environmental effects of the bituminous membrane. An application rate of 0.68 to 1.4 t/m^2 (0.15 to 0.30 gal/sq yd) is required. The soil cement should be moistened just prior to the membrane application. Sand can be spread over the bituminous membrane curing if light traffic is necessary, to prevent tracking of the bituminous material.

c. *Mixed-in-place construction.* In-place mixing is generally not used nor recommended for multi-layer construction. Plating type embankment applications are possible with the mixed-in-place method of soil cement, although again are not recommended. The basic steps in mixed-in-place construction are: soil preparation, cement addition, pulverization and mixing, compaction, finishing, curing, and protection. Following mixing, the construction techniques are essentially identical to central plant soil cement and are not further discussed under the mixed-in-place method. Although windrow type mobile pugmill mixers are used for pavement mixed-in-place construction, they are seldom used for embankment applications. Mix-in-place operations are generally performed using transverse single or multiple-shaft rotary mixers (see Figure G-8). In-place strength of the soil cement using mixed-in-place construction may be only 60 to 80 percent of the laboratory values, due partly to less efficient mixing compared to central mixing. Adding one to two percent cement is common practice to compensate for the higher variation in strength using mixed-in-place construction.

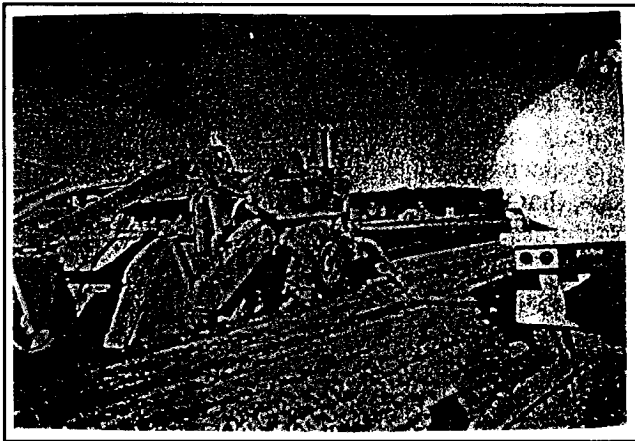


Figure G-8. Transverse single-shaft rotary mixer

(1) *Soil preparation and pulverization.* The soil is prepared by removing and replacing, or stabilizing, soft or wet areas, removing deleterious materials such as stumps, large roots, organic soils, and aggregate greater than 76.2 mm (3 in.) in size, and grading to the approximate final design profile. Most overly wet areas can be corrected by aerating and recompacting, or some type of chemical stabilization. Proper moisture content is essential for unimpeded construction traffic and for satisfactory pulverization and mixing. Dry soils may be disced and wetted by spray trucks until moisture content is near optimum for the soil cement. A moisture content near optimum may be necessary for pulverizing fine grained soils. Pulverization of soil prior to cementitious materials

spreading is generally necessary to insure uniform cement mixing. Pulverization of soils with higher fines content or higher plasticity may be difficult without proper moisture control and proper equipment.

(2) *Cementitious materials application.* Cementitious materials are distributed on the soil surface using a bulk mechanical spreader (see Figure G-9), or for smaller projects, by hand placing cement bags. Mechanical spreaders must be operated at uniform speed with a relatively constant level of cement in the hopper to produce a uniform spread of cement. Mechanical spreaders also require sufficient traction for proper distribution, sometimes requiring wetting and rolling the soil prior to spreading. Some spreaders are directly attached behind a bulk cement truck, where cement is pneumatically moved into the spreader hopper for distribution. PCA (1995) has convenient tables to convert the required cement content as a percentage by weight of oven-dry soil into a cement spread quantity in terms of weight of cement per square foot of soil surface. Cement spreading can be performed only when wind is absent and may require environmental permits. Although cement slurry spray applicators, including admixture capability, are available, they have not been widely used as yet.

(3) *Pulverization and mixing.* Most soils must be pulverized prior to mixing operations, using the rotary mixers. For mixing, single-shaft mixers require at least two passes; one to mix the soil and cement, and the second to add water. Multiple-shaft mixers handle these functions in one pass. Agricultural equipment does not generally give adequate results. In-place mixing efficiency is generally poorer than central mixed soil cement.

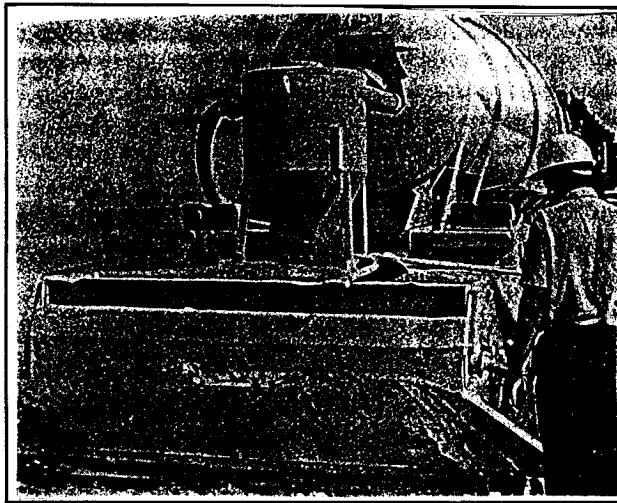


Figure G-9. Bulk mechanical spreader

(4) *Compaction, finishing, curing, and protection.* These construction techniques for mixed-in-place construction are essentially identical to those for central plant soil cement.

G-7. Quality Control, Inspection, and Testing

Adequate quality control and inspection procedures are important factors in successful soil-cement construction. Construction control procedures for soil-cement are fairly standardized. The quality of the two basic operations (soil-cement mixing and actual construction) are insured through control of four basic factors: cement content, moisture content, compaction, and curing. These factors can be controlled easily by organizing the inspection steps into a routine that fits in with the

sequence of construction steps. These steps are slightly different for central-plant construction and mixed-in-place construction.

a. Central-plant construction. The inspector checks on the following items.

(1) *Construction site and equipment.* Equipment must be clean, appropriate for the soil type, adjusted properly, and designed to preclude contamination introduction. Hauling vehicles must have protective covers where appropriate. The site should be set up to meet production and timing requirements and provide efficient traffic flow and proper separation distances for material stockpiles.

(2) *Soil.* Soil must match identification data given in the laboratory report. The inspector should check for uniformity of color, texture, and moisture. The soil should be monitored as it is stockpiled. Upon completion of the stockpile it is sampled and tested for acceptance. Gradation, specific gravity, and Atterberg limits should be tested regularly.

(3) *Cement application.* The amount of cement is specified either as a percentage of cement by weight of oven-dry soil material, or in pounds of cement per cubic foot of compact soil-cement. Pre-construction plant calibration and daily calibration checks insure an accurate mix. Different types of calibration procedures are applicable depending on the type of mixing plant used. In addition to plant calibration and daily checks of mix proportions, freshly mixed soil-cement cement content can be tested using a titration test and hardened soil-cement cement content can be tested using ASTM D 806.

(4) *Water Application.* Water is added at the central mixing plant in quantities sufficient to bring the mixture to the optimum moisture content as determined by a laboratory moisture-density test. Generally the moisture content should not be more than two percentage points below or above the specified optimum moisture. To estimate mixing water requirements stockpile moisture content is determined and additional water requirements calculated. Experienced inspectors can determine, in a qualitative way, the moisture requirements just prior to compaction by squeezing the mixture in the palm of the hand. A mixture near optimum moisture content is just moist enough to dampen the hands when packed tightly and can be broken in two with little or no crumbling. During compaction the surface of the material may dry out (indicated by a graying of the surface). Moisture is brought back to optimum by fog spraying.

(5) *Mix uniformity.* Uniformity is checked visually by noting color uniformity either at the plant or by digging a hole in the loosely placed material in the layer. If, due to lightness of soil material color, it is difficult to determine mixing, a 2 percent solution of phenolphthalein can be sprayed on a cut face of the material to determine if any cement is present. The cement in the mixture will turn treated material pinkish-red while untreated soil will retain its natural color.

(6) *Transporting and spreading.* Specified timing requirements for transporting and spreading should be monitored. Traffic patterns and possible material contamination (especially near layer edges and ramps) should be checked. Layer offset distances and layer thickness and uniformity should also be checked. The spreader should not be allowed to empty, but should be stopped while there is still mix left in the hopper. This insures uniform spreader operation.

(7) *Compaction.* Samples of the soil-cement are taken from the batch and prepared for laboratory moisture-density testing at the same time compaction is taking place. This accounts for timing parameters. In-place density testing is conducted as soon as possible after compaction in a spot where the laboratory material has been taken. Field and laboratory densities are then compared.

(8) *Curing.* Curing specifications and placement procedures should be closely monitored by the inspector. If water curing is used, the equipment must be capable of fog, rather than pressure, spraying. The surface must be kept continuously moist. Exposed surfaces should be cured for seven days. Curing times must be satisfied as well as provisions made in the case of freezing temperatures. Membrane cures must be of sufficient thickness to hold in moisture.

G-8. References

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